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Simulation-based correction approach for thermo-elastic workpiece deformations during milling processes

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Abstract

Based on the method of adaptive finite elements (FEM) a correction approach has been considered to identify the influence of thermo-elastic workpiece deformations during the production process milling.
The paper presents a simulation-based tolerance variation calculation of cutting paths, which is caused by the heat input of the machine tool. Therefore a mathematical method is developed to numerically depict the progress of the miller with different curves A(t), B(t) and C(t). These curves are used to map the state of the milling path during the production process as well as to compare the current workpiece contour and the target workpiece contour. The tool center point (TCP) correction results from mapping of time-dependent deformation fields from the FE simulation. The aim is, on the one hand, to make statements before the production about keeping the tolerance, and on the other hand, to derive other correction approaches for the adaption of the cutting path coordinates.

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1. Introduction

The manufacturing process is the center of production and is critical for the whole energy balance. Traditionally, the use of cooling lubricants ensures quality and productivity of machining processes. The energy and resource efficiency for dry machining is increased by changing from conventional flood cooling lubrication for dry machining [1].

Abandoning the cooling during the milling process leads to thermo-elastic deformations and difficult to predict geometric inaccuracies of the workpiece. The effect of omitting the cooling lubricant and the resulting almost untrammeled heat input into the workpiece are described in [2]. A decrease in production quality (size, form and position tolerances) can be avoided only by using compensation or correction strategies.

The following publications consider several correction approaches of the geometry data for the NC programming.

Different approaches exist for simulating the temperature input into the workpiece. Thus, in [3] a heat source moves into the already finished hole in order to simulate the drilling process. The thermal energy is introduced along the bore wall. This dispenses with the simulation of the real cutting process and implements a "replacement model" of the heat input. It is an idealization of the real process, but verification of the models represents an adequate solution based on experimental temperature measurements.

A similar approach has also been realized in [4]. Instead of the drill, "heated" rings can be correspondingly moved into the bore at a certain feed rate and contact conditions of heat are added to the bore wall in the workpiece. The modelling of the heat input during drilling and milling for the quantitative

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detection of thermo-elastic workpiece deformation is also analyzed in [5]. Based on extensive tests for temperature measurement while drilling and milling, the induced heat amount Q or the specific area induced heat flux density q are calculated as direct input parameters for the finite element simulation. This approach resulted in a good agreement between simulation and experiment in both simple small test pieces as well as for more complex workpieces.

In [6] the drilling process without cooling lubricant was considered. The main issue was the development of an adaptive FEM for high computing speed and its application for parameter identification for FEM calibration. Based on this method a simulation tool for a correction algorithm was investigated for drilling positions and out-of-roundness quantifications.

In Germany several projects are carried out for various studies of the heat input into the workpiece and the machine tool. The DFG project SPP 1480 focuses on the thermal effects of the whole workpiece. The goal is, to avoid or to compensate already in production planning the resulting inaccuracy from the process of manufacturing by simulation-based methods [7]. For example, in [8] the temperature input is analyzed mathematically in the workpiece during milling with a simulation model.

As part of the Collaborative Research Centre Transregio 96 (CRC TR 96) studies of the thermo-elastic behavior of machine tools are performed. Bases for correction and compensation approaches are examined, which will lead to an increase in manufacturing precision considering the energy efficiency aspect [9].

Literature research gives a short overview about the thematic of thermal phenomena during cutting processes. This paper presents the temperature distribution and the thermo-elastic deformation of the workpiece during the process of an even milling path. At first the numerical optimization problem of the milling process will be delineated. Subsequently follows the description of the mathematic modelling of the heat transfer and material removal in the finite element mesh. After than the simulation results will be described.

2. Characterization of the numerical problem - milling process

The toolpath of the milling process can be considered as a geometrical curve in Eq. (1), so that each point in time t from $[0,t_{end}]$ is allocated to a point x=x(t) with x in R^3.

$$\Gamma : [0, t_{end}] \rightarrow \mathbb{R}^3 \tag{1}$$

In the real cutting process unwanted thermo-elastic deformation occurs, this phenomenon can be characterized with mathematical mappings. Considering a real milling contour, it can formally define three curves A(t), B(t) and C(t). Each curve describes another condition of the milling process:

- Target workpiece contour A(t) describes the target-geometry of an arbitrary milling contour equivalent to the technical sketch or CAM/CAD models from the constructor.
- Milling curve B(t) describes the real milling contour which is adjusted during the working process with less or without any cooling lubricant on the real machine.
- Current workpiece contour C(t) describes a slightly adjusted contour which leads to a better result for the targeting contour A(t).

With the assumption that enough cooling lubricant is used in the working process, all three curves correspond to one another in the theoretical ideal case A(t)=B(t)=C(t). In reverse assumption, without any cooling lubricant all three curves are unequal.

If the mapping of the "target curve A(t)" on the resulting end product B(t) is simulated accurately, it is possible to formulate an optimization problem:

Find curve C(t) so that the magnitude |B(t)-A(t)| conforms the defined tolerance. The calculation of the mapping A(t)→C(t) is sufficiently complicated because it contains solving the time-dependent temperature distribution T(t,x) and its impact on the thermo-elastic deformation U(x,t) as an evolution equation for t from the time interval (0,tend). Subsequently follows the complete cooling process ($T(t_{end},x)$ is zero in all points of the workpiece) and the calculation of the displacement (current geometry after cooling) at the end.

The aim of this approach is to determine the curve B(t) numerically in the first step with the adaptive FEM. The curve B(t) results after using the target curve A(t) and quantifies deviations between A(t) and B(t). In the second step the optimal curve C(t) should be calculated to correct the thermo-elastic deformation. The criterion of the resulting minimal optimization problem is ||B(t)-A(t)||→min so that the real curve B(t) after cooling of the workpiece is as close as possible to curve A(t).

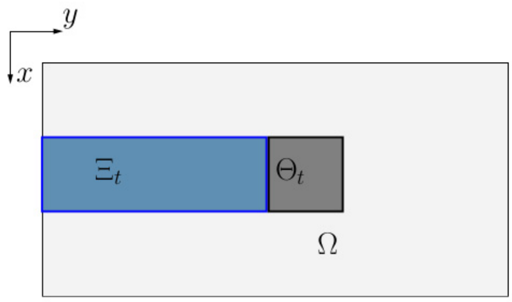

Figure 1 Workpiece surface with different domains

3. Modelling of the heat transfer and material removal

The raw workpiece before the milling process can be seen as a domain Ω from R^3. For modelling the material removal and heat induction some subdomains Θ_t of Ω can be defined as follows.

At first there is a time-dependent subdomain Θ_t which defines the current intrusion into the workpiece at time t. Furthermore the full path Ξ_t of the milling tool from time 0 up to time t can be defined as the union of the subdomains Θ_t, i.e. in Eq.(2).

$$\Xi_t = \bigcup_{\tau=0\cdots t} \Theta_\tau \tag{2}$$

For a striking illustration of the domains Θ_t, Ξ_t, and Ω see Fig. 1. The heat induction can be modeled as a time and space-dependent source term in the heat equation. Thus it exists a heat source function h(t,x) which is zero outside Θ_t and nonzero inside, i.e. Eq. (3), where h_m is a constant nonzero heat source, given in [W/mm³].

$$h(t,x) = \begin{cases} h_m & \text{for} \quad x \in \Theta_t \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

This function is implemented in the finite element code [10] and will be called during the assembling of the element load vectors for the heat equation.

The material removal interacts with the part of the above domain Ξ_t which enlarges with the time t. To approximate the material removal in the finite element program a special technique is used, the so called “element zero setting”. This technique simulates the removal of elements by zeroing the element material parameters, especially the elastic modulus, the heat transfer coefficient, the density and heat capacity. Such a “zero element” behaves in the finite element simulation as if it did not exist.

For example, the elastic modulus E becomes now a defined piece by piece, time-dependent function such as Eq. (4), where E(x) is the normal, time independent elastic modulus, in cases piecewise constant in material areas. In the same manner the other material parameters such as the heat transfer coefficient, the density and the capacity become time and space-dependent functions.

$$E(t,x) = \begin{cases} 0 & \text{for} \quad x \in \Xi_t \\ E(x) & \text{otherwise} \end{cases} \tag{4}$$

These functions are implemented again in the finite element code and will be called during the assembly of the element matrices for the thermo-elastic coupled heat dependent functions.

In the finite element code, which can solve time-dependent thermo-elastic deformation problems, some more adaptions are needed. The mesh refinement must allow special refinement of the milling zone. Therefore some preprocessing steps will be carried out by element diving and mesh refinement before starting the real simulation with time stepping. During the simulation some adaption of the output for the postprocessing is used to achieve the important results of the simulation, especially the displacement along the contour of the milling zone.

Together with these adaptions the length of time step must match the grain size of the mesh in such a way that during the time steps only whole elements will be zeroed. By choosing an appropriate refinement in the preprocessing steps and setting the total number of time steps to a power of two this is fulfilled.

Table 1. Displacement of discrete cutting path points along the right hand side

y [mm]	u_x[µm]	u_y[µm]
0	0.0	0.0
50	7.259	11.733
100	18.625	24.669
150	19.254	39.487
200	27.921	38.353

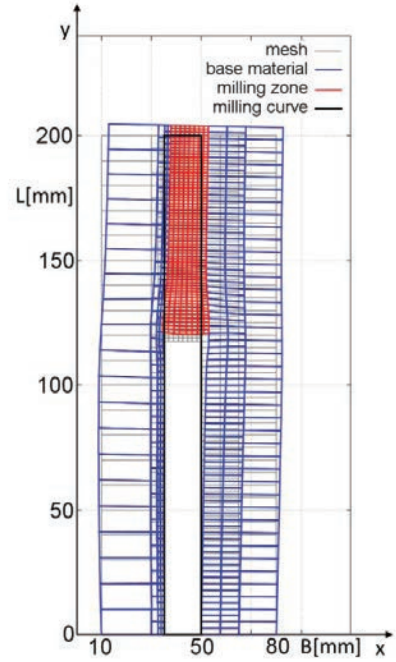

Figure 2 Time-dependent and space-dependent displacement in slot milling

4. Numerical results for the thermal effects

For the FE simulation a simple workpiece is constructed as a hexahedron. The material of the workpiece is assembled of different material areas for a better demonstration of the thermal effects during the heat input. On the left hand-side of the workpiece is a material part with a bigger coefficient of thermal expansion than in the rest of the workpiece. The measurements of the edges are 70mm in the x-direction, 200mm in the y-direction and 50mm in the z-direction. The milling zone is in the middle of the workpiece; see in Fig. 2 the red part with the adaptive mesh refinement. The clamping is defined in the simulation model as Dirichlet boundary condition in the front of the workpiece. This illustration presents the undeformed start mesh in thin grey lines with the integrated milling curve in bold black lines. The deformed mesh is shown in blue lines, which presents the thermo-elastic displacement of the workpiece. The conclusion of the simulation is that the mill cuts too much material from the workpiece during the working process without cooling lubricant.

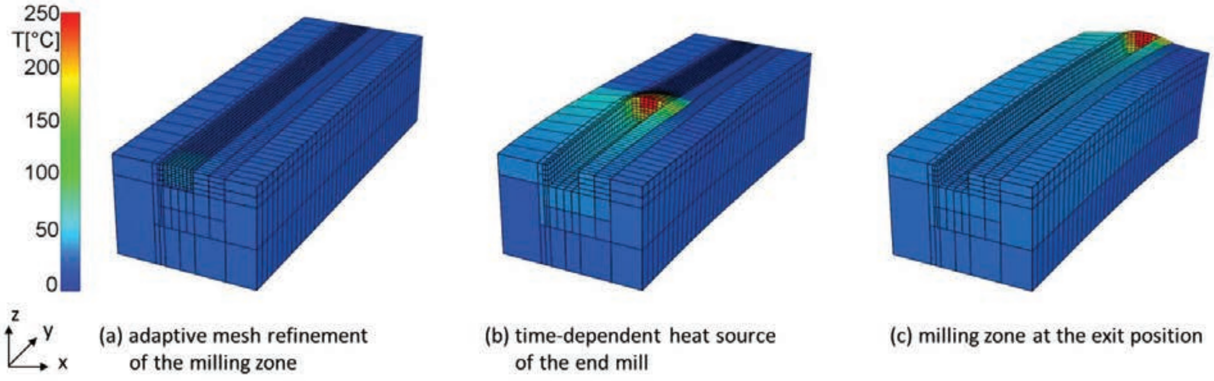

Figure 3 Time-dependent and space-dependent temperature distribution and displacement in slot milling

In a first approximation the correction coordinates for the NC control can be deduced from this result. Table 1 lists these values.

The progress of the time-dependent simulation is shown in the three snapshots in Fig. 3a, b and c. Fig. 3a presents the whole model with the adaptive meshed milling zone. After some time-steps the heat source has moved to the middle of the mesh and all elements before are deleted, see Fig. 3b. The thermo-elastic deformation increases with the forward motion of the heat source. Finally Fig. 3c demonstrates the thermal effects in all three coordinate axes, which have to be compensated in the real milling process.

5. Conclusion and Outlook

This paper describes a finite element based simulation approach for milling problems to calculate thermo-elastic deformations of workpieces.

Thus, a mathematical approach was considered to optimize the cutting path through three curves A(t), B(t), and C(t). In the first step this simulation is carried out with the main focus on the thermo-elastically induced deformation of the milling zone to recognize the deviation of the desired milling curve from a real milling curve. The implementation of the heat source and material removal was described in detail. The outcome is the milling error which should be corrected by the presented optimization method. Based on these results further research is planned to develop an optimization algorithm for milling curve adaption. Using this optimization approach an adjusted milling curve will be computed, so that after cooling down of the workpiece the resulting milling curve matches the planned milling curve.

Furthermore some quality estimations will be computed, for example, the deviations of milling curve sizes, unwanted material deformations and stress peaks. The used adaptive refinement is mandatory to achieve realistic results, especially for the computing stress peaks.

By collaborative work within the CRC TR 96 experimental investigations are planned to verify the theoretical and computational conclusions.

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